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I/J BAND LOW-COST CROSSED-FIELD AMPLIFIER.(U)

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Research and Development Technical Report

DELET-TR-77-2642-F

I/J BAND LOW-COST CROSSED-FIELD AMPLIFIER

Robert R. Moats
NORTHROP DEFENSE SYSTEMS DIVISION
Electron Tube Section
Des Plaines, IL 60018

JUNE 1979

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This program is directed toward development of an I/J band, linear format, injected-beam crossed-field amplifier (IBCFA) for electronic warfare. The IBCFA should be capable of power output of 1000 W peak, 200 W average, between 8.5 and 17 GHz with 20 dB gain. A laser-cut shaped-substrate meander line is used. Performance in an E/F band IBCFA was evaluated, for which the objective performance in the 2-4GHz

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band is 3.0 kW peak power output, 1.0 kW average power output, also with 20 dB gain. In addition, a gun for I/J band was designed.

The technology for constructing meander circuits on laser-cut shaped substrates bonded to co-expansive ground planes has been established. Operating CFA's have been built and tested in E/F-band, and cold test meander circuits have been built in I/J-band.

The first E/F-band operating CFA using the shaped-substrate meander line, and other parts common with a standard E/F-band CFA design, was built and tested. Performance was comparable with a typical CFA of standard design, slightly lower in efficiency at mid band and approximately the same over the remaining part of the 2-4 GHz band. The second E/F band operating model was limited in peak power, apparently from RF arcs for reasons not yet determined.

An unbrazed I/J-band cold-test model was built, and measurements of delay ratio, coupling impedance, and attenuation were made. Results showed that a reduction of pitch and a thinner substrate are necessary for an efficient I/J band tube. A brazed model with the same pitch but with the desired thinner substrate showed anomalous values of delay ratio and excessive RF losses. Further investigation of the cause is necessary.

An important problem remaining is related to the fragility of the I/J-band laser-cut substrate. Improvements in laser cutting and in dealing with the fragility of the resulting pieces are necessary. An experiment in laser-cutting after a blank substrate is bonded to the co-expansive ground plane indicates that this alternative merits further investigation, and is a desirable approach to fabricating I/J-band circuits.

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SECTION I

INTRODUCTION

The effort in this program was directed toward the development of a high-power broadband low-cost I/J band linear format injected-beam crossed-field amplifier (IBCFA) for electronic warfare. A laser-cut shaped-substrate meander line circuit was used. Performance is an operating E/F band tube was evaluated, and cold-test I/J band meander lines were built and tested. In addition, a gun design for I/J-band was extrapolated from an existing crossed-field gun design.

A major cost factor in present IBCFAs is the meander slow-wave structure, which incorporates a meander strip of copper and one separate ceramic insulator supporting each segment of the meander. By replacing the set of insulators with a single shaped substrate which can be manufactured at moderate cost, very substantial cost savings in both time and labor can be achieved. The shaped-substrate concept was originated by U.S. Army ERADCOM personnel, and has been the subject of study by C. Bates and J. Hartley of ERADCOM.

The objective specifications for the E/F band operating model are as follows:

Frequency	2-4 GHz
Peak Power Output	3 kW
Average Power Output	1 kW
Efficiency	35%
Gain	20 dB
Cathode Voltage	7 kV (max)
RF Input Impedance	50 ohms

The cold-test circuits built for I/J band were directed toward the achievement of the following objective specifications:

Frequency Range	8.5-17 GHz
Peak Power Output	1 kW
Average Power Output	200 W
Efficiency	30%
Gain	20 dB

Cathode Voltage	8 kV, maximum
RF Input Impedance	50 ohms

In a previous program for ERADCOM[1], IBCFAs were designed, built, and tested using simulated shaped-substrate meander lines built with conventional technology. In this program, actual one-piece shaped substrates were used, and one of the major portions of the effort was directed toward the technology of the meander line on such a substrate, and the mounting of line and substrate on a coexpansive ground plane. In other respects, the technology of production IBCFA's was used as much as possible.

The technology of manufacture of the shaped-substrate ceramic was crucial to the successful performance of this project. It is clear that conventional methods of making a single-piece ceramic substrate are inadequate, in terms of both feasibility and cost. ERADCOM personnel performed exploratory work on laser cutting of ceramic substrates in a ladder configuration, and a significant measure of success was achieved. The configuration of a meander line on a ladder-shaped substrate is shown in Figure 1. In previous work performed by Northrop under ERADCOM sponsorship, the difference between the electrical properties of a meander line on a simulated meander-shaped substrate and on a simulated ladder-shaped substrate were found to be insignificant. A meander-shaped substrate is impractical from a mechanical point of view, unless laser cutting can be performed after the substrate is bonded to the ground plane. This project was based on the ladder-shaped substrate as a starting point for demonstration of operating IBCFA's in E/F band and cold-test meander lines on ladder-shaped substrates and coexpansive ground planes in I/J band.

[1]Research and Development Technical Report No. ECOM-75-1343-1, Low Cost Crossed-Field Amplifier, Final Technical Report, prepared by Northrop for U.S. Army Electronics Command, June, 1977.

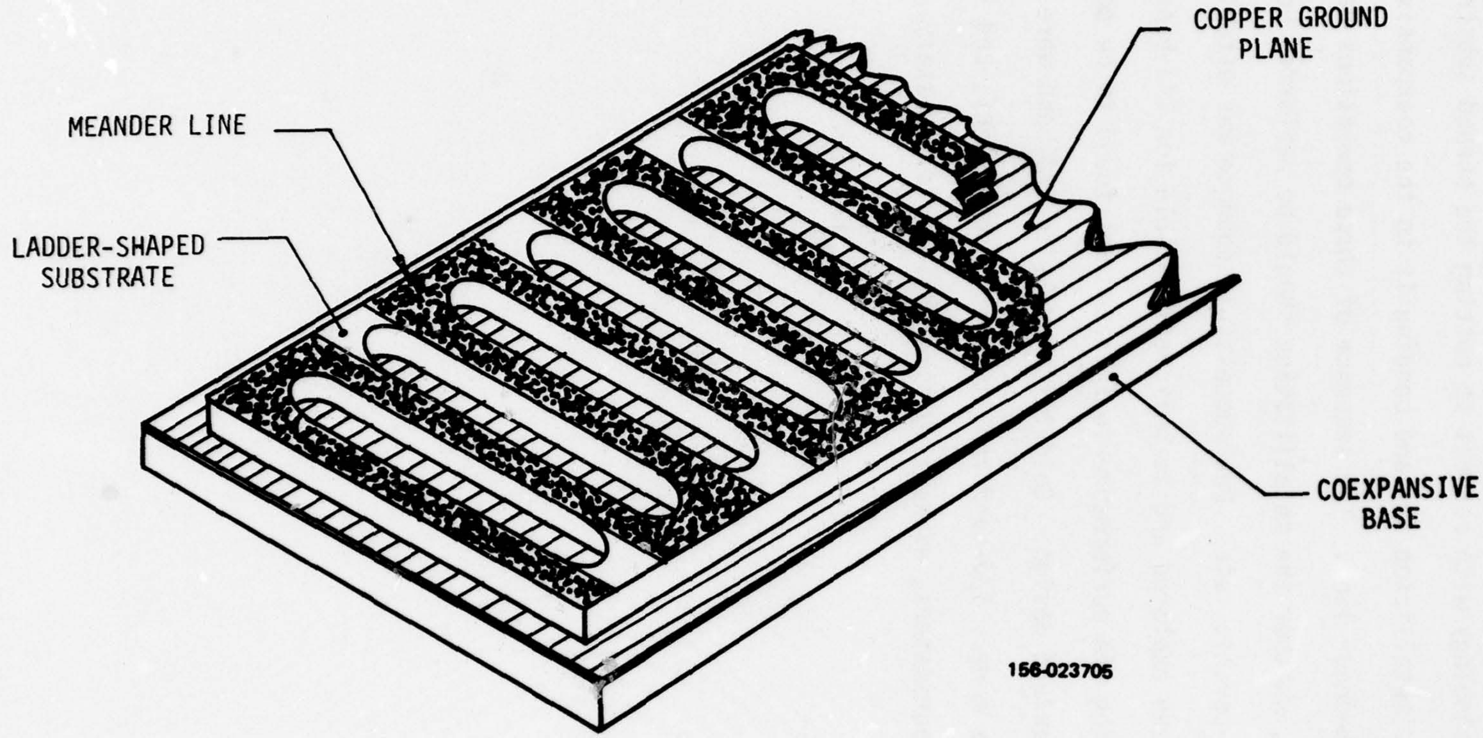


Figure 1. Meander Line on Ladder-Shaped Substrate and Coexpansive Base.

For realization of E/F and I/J band models, it was necessary to develop suitable technology with respect to cutting the shaped substrate from beryllia ceramic, metallizing it, and bonding it to the coexpansive ground plane and to the meander line. The sequence of these operations had to be determined, e.g., whether the metallization should be performed before or after cutting the ceramic, etc. One successful sequence was established, and another has been explored and is believed feasible for I/J-band.

Operating CFA performance in E/F-band was found to be comparable with CFA's of standard design. Cold-test models in I/J-band were constructed and measurements made. I/J-band results were inconsistent, and further study of electrical parameters, especially attenuation, is necessary.

SECTION II

TECHNOLOGY

2.1 Bonding to Coexpansive Ground Plane

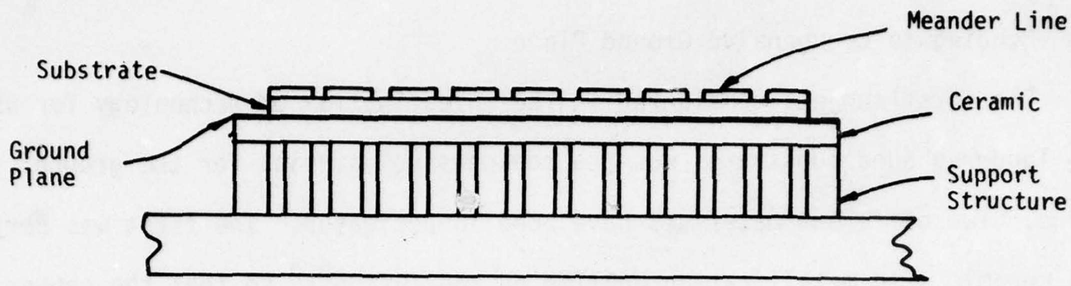
The first subject considered in the investigation of technology for using ladder-shaped substrates was the coexpansive material for the ground plane. Two different materials have been investigated. The first was beryllia ceramic with metallization applied by sputtering[2,3] so that the copper layer is several skin depths thick to form a good RF ground plane as shown in Figure 2(a). The second is a composite material consisting of porous tungsten infiltrated with copper. By a proper choice of the proportion of copper and tungsten, the thermal expansion of the resulting composite material can be made to match the thermal expansion of beryllia ceramic very closely. This is shown in Figure 2(b). A third configuration of the coexpansive ground plane is a sandwich consisting of metallized beryllia ceramic facing the substrate and copper-tungsten composite facing the supporting structure, as in Figure 2(c). The ceramic in the sandwich is more rugged than the laser cut ladder and provides an ideal coexpansive match to it. The composite has higher mechanical strength for attachement to the supporting structure.

The sputter metallization process is preferred to others because of the high tensile strength which has been demonstrated to be consistent[4], the low

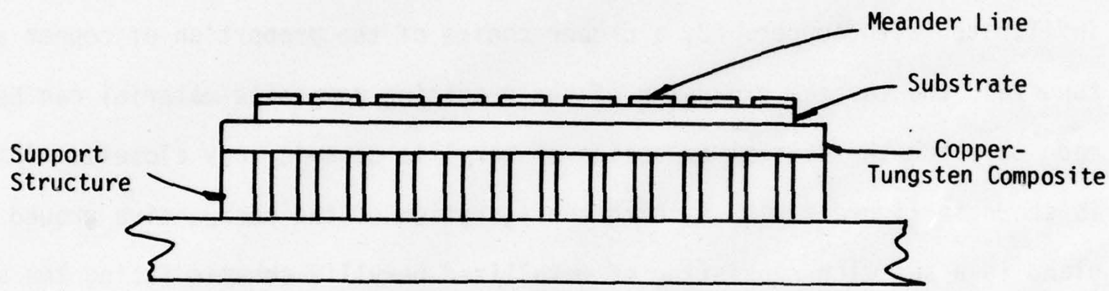
[2]M.L. Cooke, R.R. Moats, "Influence of Metal-Ceramic Bonding Processes in Crossed-Field Amplifier Performance", Conference Record of 1973 Conference on Electron Device Techniques, pp. 76-83, IEEE, New York.

[3]Final Technical Report, Metal-Ceramic Bonding, Report No. AFAL-TR-77-86, prepared by Northrop for U.S. Air Force Avionics Laboratory, May, 1977.

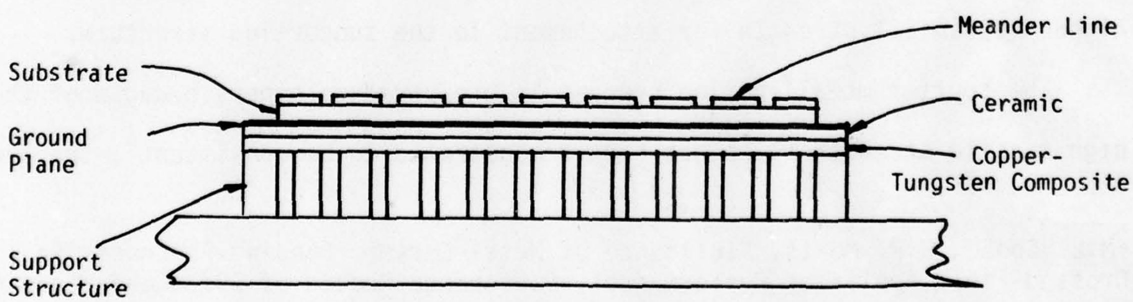
[4]*Ibid*.



(a) Coexpansive Ground Plane: BeO Ceramic, metallized



(b) Coexpansive Ground Plane: Copper-Tungsten Composite



(c) Coexpansive Ground Plane: Sandwich of Metallized BeO Ceramic and Copper-Tungsten Composite

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Figure 2. Three Possible Configurations for Coexpansive Ground Plane

RF losses[5], and the absence of a glassy interface layer present in other metallizations which introduces a significant thermal barrier. The sputter metallization includes a layer of titanium about 250 Å thick, a layer of molybdenum of 1500 Å or greater thickness, and a layer of copper which is usually a few micrometers thick. The molybdenum, which will not alloy with copper, forms a barrier against copper diffusion into the beryllia ceramic. For I/J-band, it is desirable that the thickness of molybdenum should be less than 2000 Å[5], and a nominal value of 1500 Å has been chosen for the I/J-band substrates. Bonding is accomplished by copper-to-copper diffusion under pressure and high temperature (of the order of 1000°C) in hydrogen. The resulting metal-to-ceramic interface has been found to have RF losses substantially equal to those of copper alone, and the thermal impedance at the interface is very small.

As to the coexpansive composite material itself, two sources have been used. One material is Elkonite*, and the other material was supplied by Kometco, Inc. The principal difference is that the Kometco material is made using OFHC copper, while the copper in Elkonite is not so specified. In addition, commercially available Elkonite is 57% tungsten by volume; the initial pieces of material supplied by Kometco were 62% tungsten by volume, and the last received pieces, those by experience giving the best match to the ceramic, were 68% tungsten by volume.

Samples of both the Kometco material and Elkonite in the form of 1/32-inch thick plates were tested for vacuum integrity. Both were vacuum tight, as measured on a helium mass-spectrometer leak detector, before firing. After firing at about 1000°C in hydrogen, the Elkonite was porous to helium, while the Kometco material remained vacuum tight.

[5]Cooke, Moats, op. cit.

*Trademark, P.R. Mallory Co.

The first bonding experiments were made using pieces of laser-cut beryllia substrate pieces (scrap from an ERADCOM order). One of these pieces was sputter metallized, then bonded by copper-to-copper diffusion to a similarly metallized beryllia ceramic coupon. The bonding appeared excellent, and no apparent degradation was observed after 25 thermal cycles between room temperature and 500°C in hydrogen. A second piece of ladder substrate was bonded to a piece of Elkonite. (A thin layer of copper on the Elkonite is required.) The bond was good and there was no evidence of fracture of the ceramic. This assembly was temperature cycled in hydrogen, 10 cycles between room temperature and 700°C, with no apparent degradation. A third piece of laser-cut substrate material, nearly equivalent to a full-length line, was similarly bonded to a supporting piece of Elkonite, which was then brazed to an array of copper posts as illustrated in Figure 3. (The ceramic between the substrate and the Elkonite was of course not present). This assembly is shown in Figure 4. The assembly was thermal cycled 10 times to 700°C and back to room temperature, with no evident deterioration. Finally, examination of a metallurgical cross section of the ceramic-metal interface showed that the bond was still excellent. (See Figure 5.)

In the assembly shown in Figure 4 there was some evidence of warpage, suspected to be a bi-metal effect due to the difference in expansion between copper and Elkonite. A test with the Elkonite plate thickened for added stiffness indicated no improvement. However, when the support posts were made thinner over one-quarter of the length of the assembly at each end, flatness was within 0.001" over the total length. The assembly with thinner posts is shown in Figure 6.

Because of the success of these experiments, it was considered feasible to bond the substrates directly to the copper-tungsten composite ground plane, as in Figure 2(b).

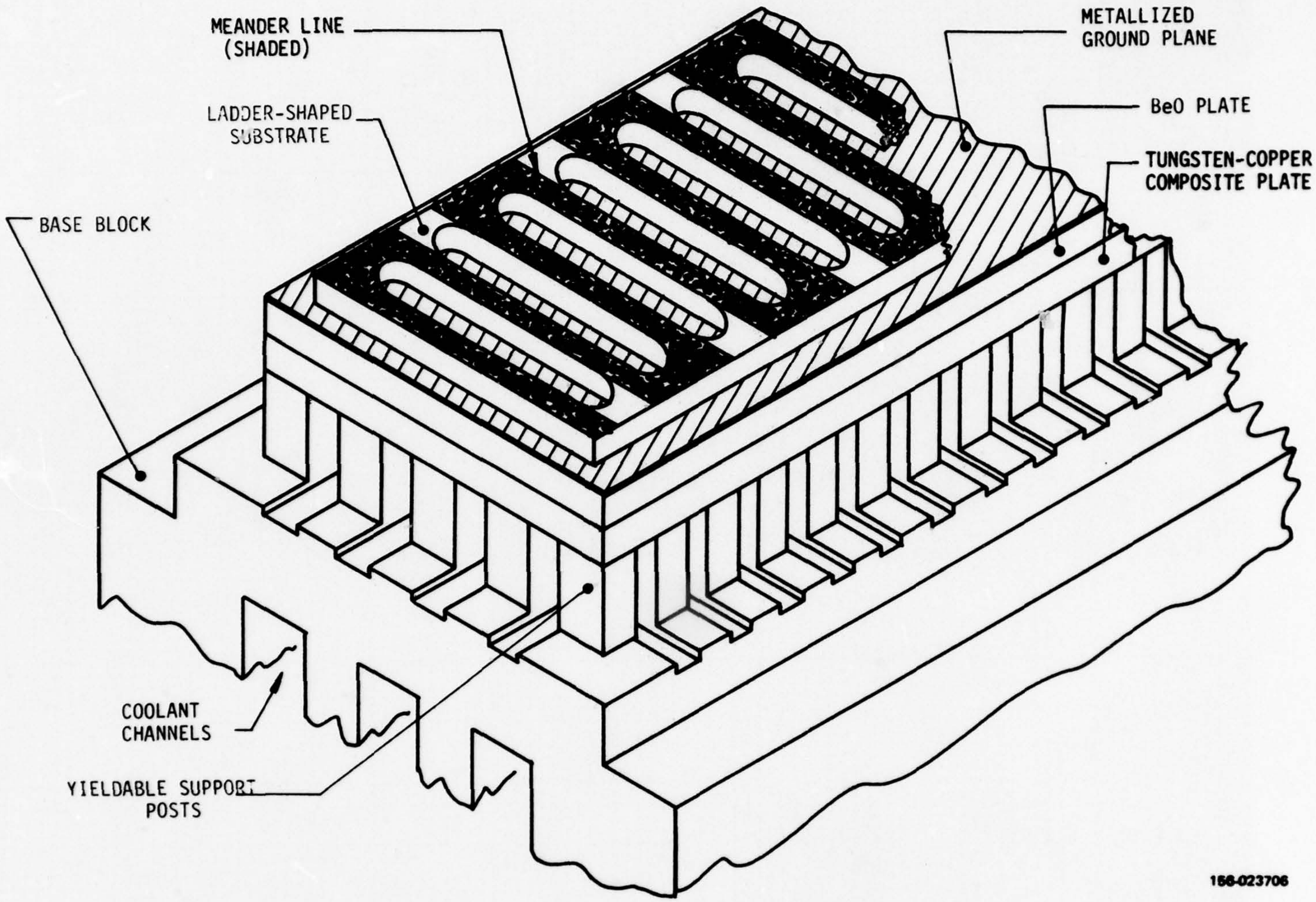

Figure 3. Laser-Cut Ladder Substrate on Coexpansive Ground Plane Supported on a Base Block of Conventional CFA.

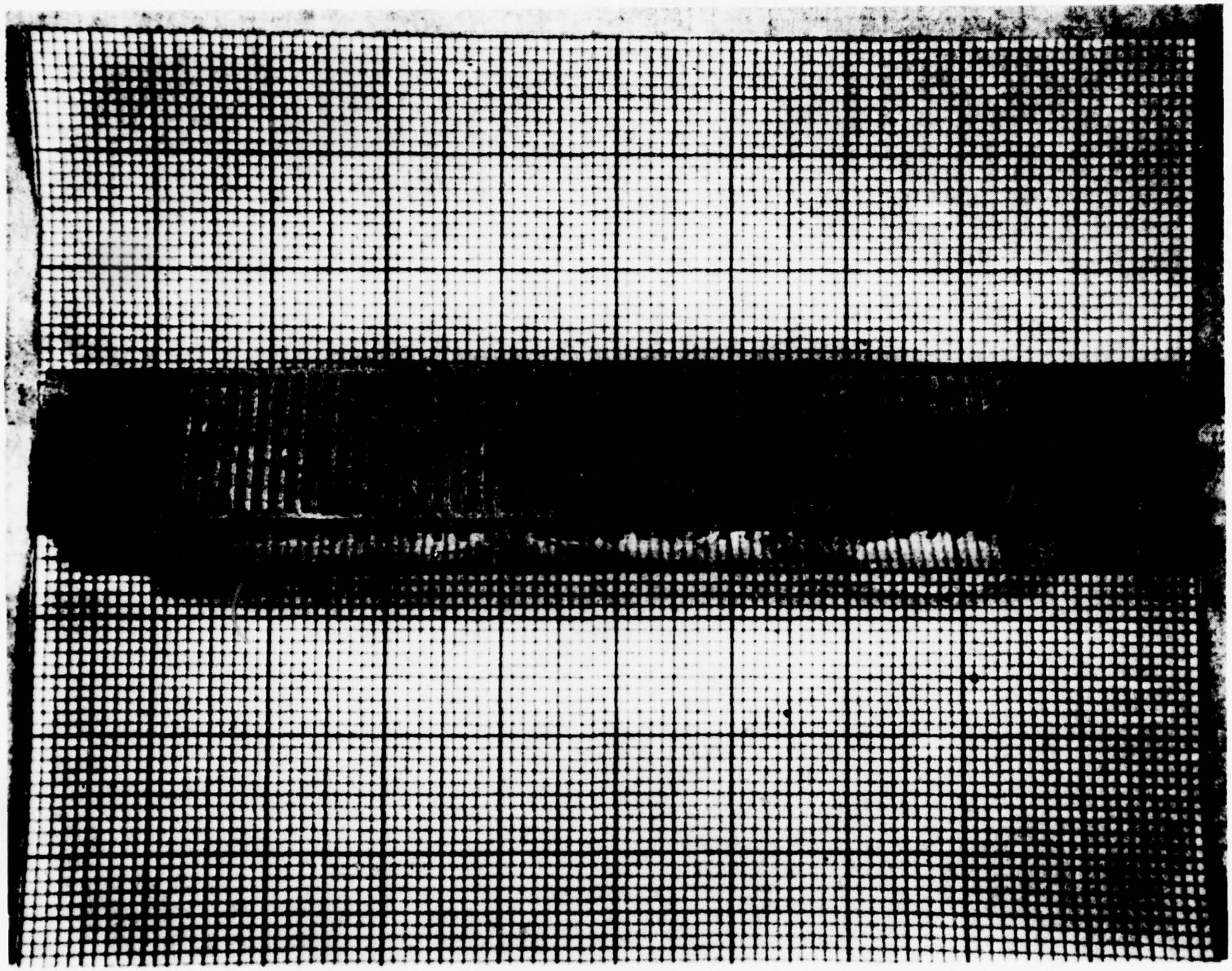

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Figure 4. Mock-up Test of Ladder-Shaped Substrate on a Coexpansive Base and Yieldable Posts.

Figure 5. Metallurgical Cross-Section of Diffusion Braze After Thermal Cycling.

Figure 6. E/F-Band Cold Test Model with Added Slotting of Support Posts.

2.2 Cutting Substrate and Forming Meander.

In making meander lines on ladder substrates, the four operations which must be accomplished, not necessarily in the following order, are:

- Laser cut slots
- Sputter metallization
- Form meander pattern
- Braze to coexpansive base

A number of possible sequences have been investigated. The initial approaches involved laser-cutting the substrate first. No successful method of shielding the slots during subsequent metallizing nor of removing metallization from the slots selectively was found. Laser cutting through metallization is not feasible because of the high reflectivity of copper. If the substrate is metallized and then a meander pattern is photo-etched on one side, it is possible to laser cut the slots in the gaps between meander bars. Registration of the laser cutting with respect to the meander pattern was found to be accurate. The resulting metallized ladder is then bonded to the coexpansive ground plane. This sequence was used in the operating E/F-band CFA's and the final cold-test model in I/J band. One other sequence, in which the laser cutting is performed after the substrate is bonded to the coexpansive ground plane, appears to merit consideration. Some initial experiments with respect to such an approach are described below.

In laser cutting the slots after metallizing, tiny globules or burrs of ceramic appeared at the boundaries between the metallizing and the slots. In all models so far built, the metallizing has been thin, with a copper photoetched meander to be bonded on top of the meander-shaped metallization on the substrate. The globules had to be removed by hand for the structures which were built and tested.

A serious problem is the fragility of the laser cut structures. Breakage occurs during handling and during the bonding to the co-expansive substrate. If an uncut coupon with appropriate metallizing pattern is bonded to the ground plane and then laser cut, the fragility problem is greatly relieved. The concept is that the laser cutting will stop when the laser beam strikes the copper-tungsten composite material and is reflected. Some experimental assemblies were made of blank substrates metallized only on one side and bonded to a co-expansive ground plane. Laser cutting efforts on the pieces of E/F band dimensions were not successful. The great disadvantage is that all of the material in the slots must be vaporized; it is no longer possible to cut around the periphery of the slots. For I/J band, where fragility is greater, and the substrate thinner than E/F Band, it is more reasonable to remove all of the material by vaporizing it.

Some samples of laser cuts for I/J-band in substrates already bonded to the ground plane are shown in Figure 7. Three series of slots are shown representing different settings of the laser, different feed rates, etc. The first is at the bottom, the second at the upper left, and the third at the upper right. The difference between the second and third is that in cutting the third series, the initial cut was in the center and cutting progressively moved toward the edges. Spot size was about 0.002" diameter and the slot width is about 0.008". The quality of the cutting in the third series is comparable with results obtained in cutting before the substrate is bonded to the ground plane. Therefore this approach will be pursued further for I/J band.

Of the three samples of 0.006" thick ceramics bonded to 0.030" thick ground planes, two showed hairline cracks after bonding. The other showed slight bowing in the direction indicating that the composite material had too high a value of thermal expansion, i.e. too much copper. The mix of these

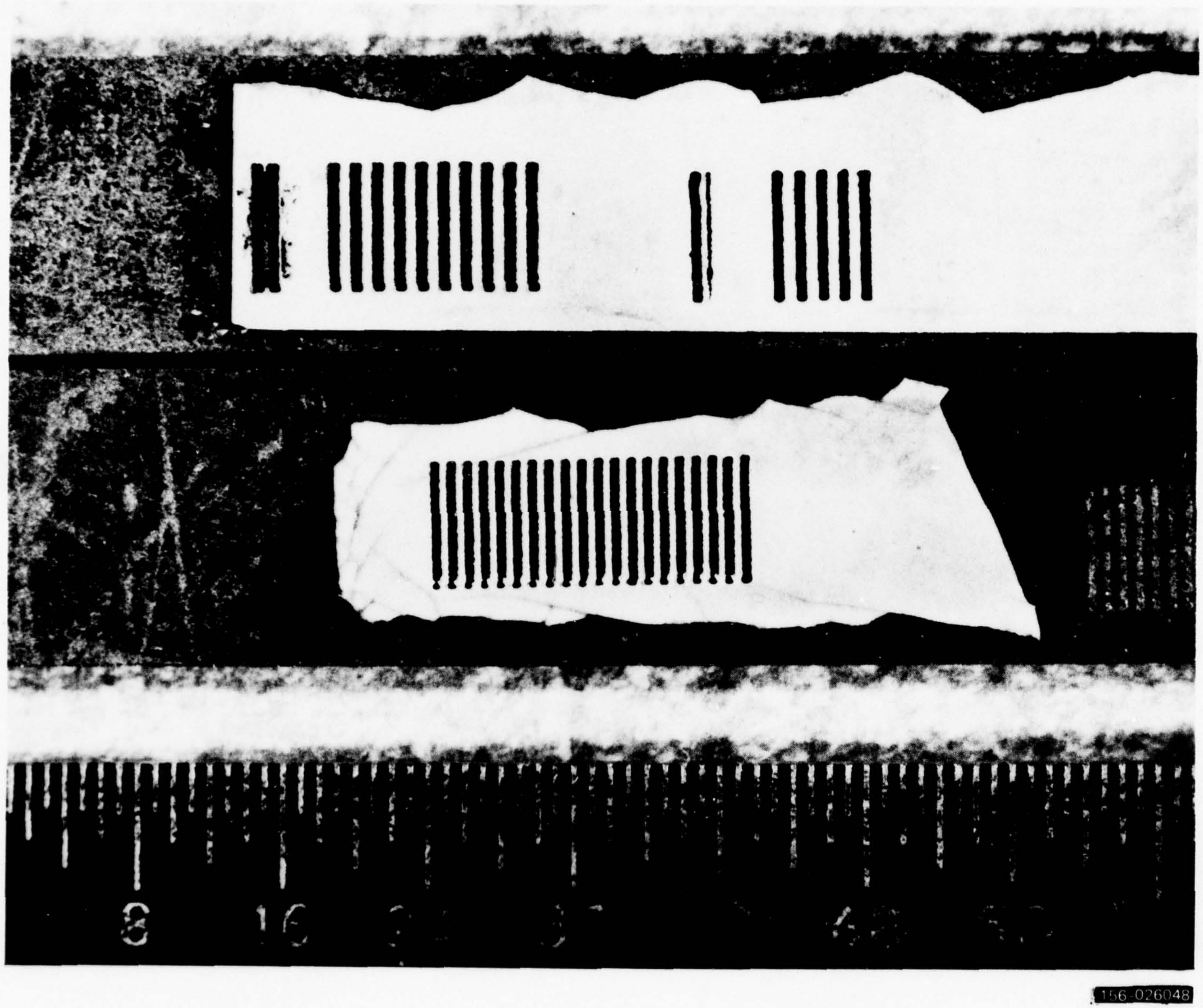


Figure 7. Laser Cutting of Substrate After Bonding to Ground Plane.

copper-tungsten composite pieces was 62% tungsten by volume. These observations support the need for using 68% tungsten in the future. The hairline cracks did not interfere with the laser cutting experiment, and did not grow during laser cutting.

SECTION III

E/F BAND IBCFA

3.1 Design of Circuit

The meander line circuit design of the projected operating IBCFA in E/F band was scaled from data supplied by ERADCOM personnel. The ERADCOM version was scaled in over-all width from 0.500" to 0.460" to adjust the frequency corresponding to 90° phase shift from 3.2 to 3.5 GHz. The pitch, which would be changed from 0.050" to 0.046", was actually made 0.048", thus reducing the delay ratio (increasing phase velocity). The substrate thickness remained at 0.017". The circuit thickness used was 0.005" instead of 0.001" to allow more familiar metallizing and bonding technology.

3.2 Mechanical Design

The width of the circuit is comparable with the second design (flat substrate) made during the previous contract, No. DAAB07-75-C-1343 (Reference No. 1), and with a standard E/F band IBCFA. Therefore, a substantial number of parts are common with existing designs. The gun is similar to that used in the first design (simulated shaped substrate) of the previous contract, except that its width is adjusted accordingly. The base structure is like that of the tubes of the previous contract, except that the coexpansive structure is supported on "posts", as in Figure 3.

The input and output connections are coaxial, and the input and output window seals are identical to those used on existing IBCFA's. The coaxial output (or input) passes through the line support members and connects to the line as shown in Figure 8 (cross section) and Figure 9 (isometric). The first bar of the substrate is wider at one end, to allow a suitable hole through the substrate for the center conductor to be attached. The opposite side of the substrate must be metallized in a pattern such that there will be no metal-

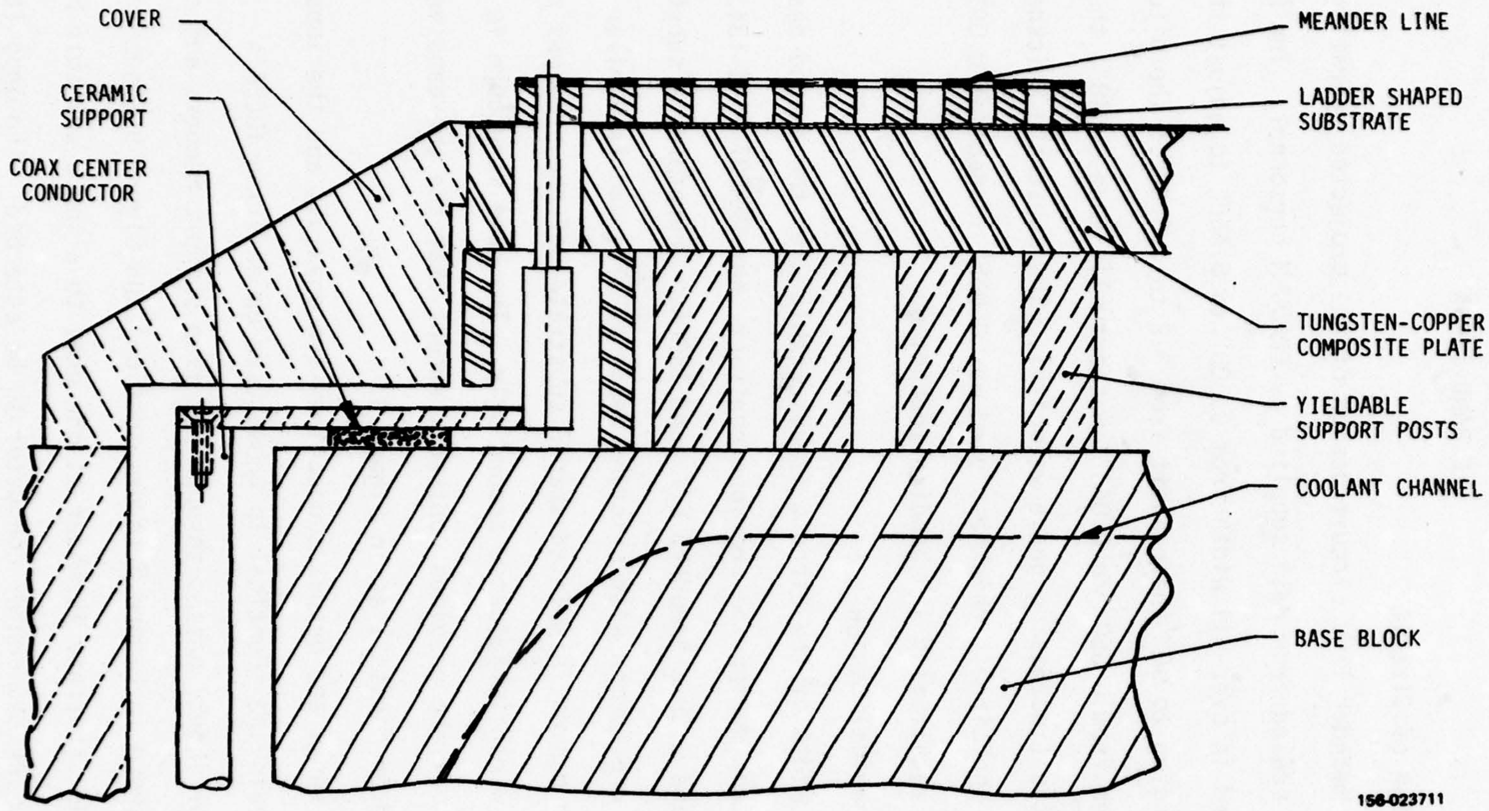


Figure 8. Cross-Section of Attachment of Coaxial Line to Meander Line on Ladder-Shaped Substrate.

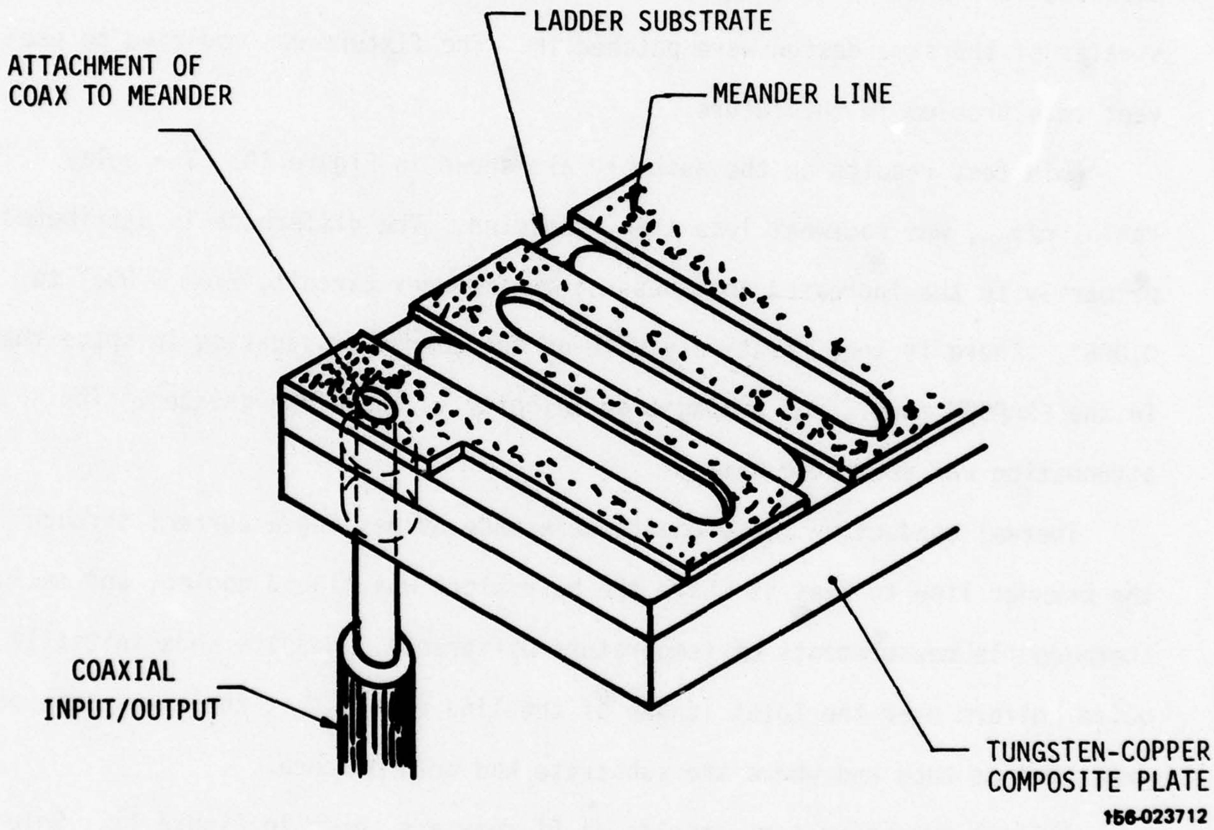


Figure 9. Attachment of Coaxial Line to Meander Line on Shaped Substrate.

lization over the coaxial region. The two 90 degree bends, as shown in Figure 8, allow a little flexing to accommodate thermal expansion, while position is maintained by the ceramic support.

3.3 Operating Model No. 1.

An operating IBCFA was constructed using the design described above. When the ladder-shaped substrate was bonded to the ground plane, the bars on each end fractured. The broken bars were filed off, and pieces of broken substrates of the same design were patched in. The fixture was modified to prevent this problem in the future.

Cold test results on the assembly are shown in Figure 10. The delay ratio, c/v_{ph}, was somewhat less than predicted. The difference is attributed primarily to the increased thickness of the meander circuit, from 0.001" to 0.005". There is thus relatively more of the energy propagating in space than in the ERADCOM model, and propagation velocity is therefore greater. The attenuation was about the same.

Thermal conduction measurements were made by passing a current through the meander line to heat it while the base block was liquid cooled, and making thermocouple measurements of temperature difference. Results were initially quite uniform over the total length of the line except that there was some degradation at each end where the substrate had been patched.

Initial operating test results at 5% duty are shown in Figure 11. Sole voltage was set at three different values to cover the octave bandwidth range in the same manner as specified for the standard RW-619 CFA made at Northrop. For comparison, results for a typical RW-619 are also shown. Only in the center of the band is power output significantly less, and this is in part due to lower beam power. No significant spurious signals were observed (i.e., greater than -20 dB with respect to main signal).

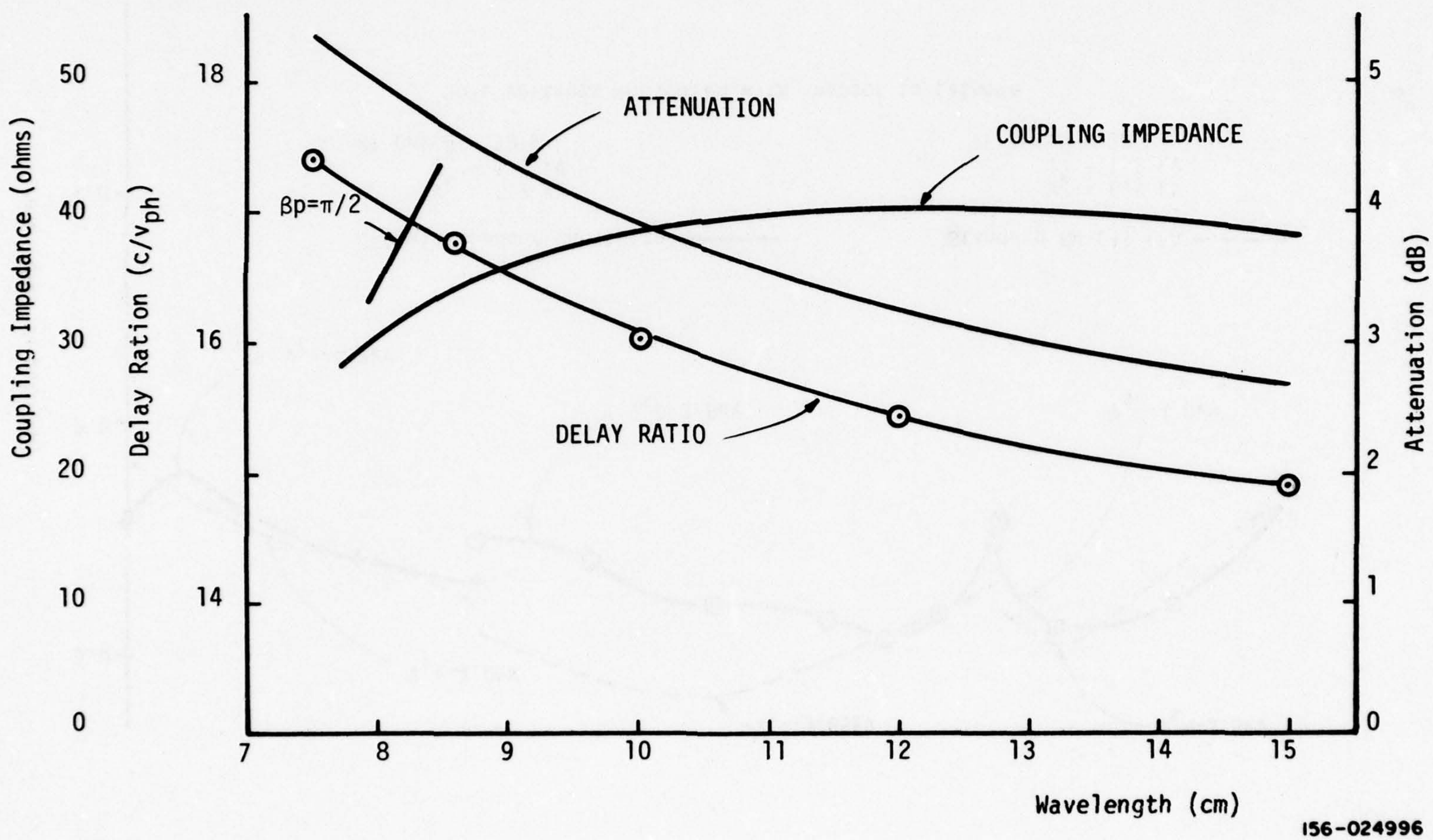


Figure 10. Cold Test Data for Operating CFA No. 1.

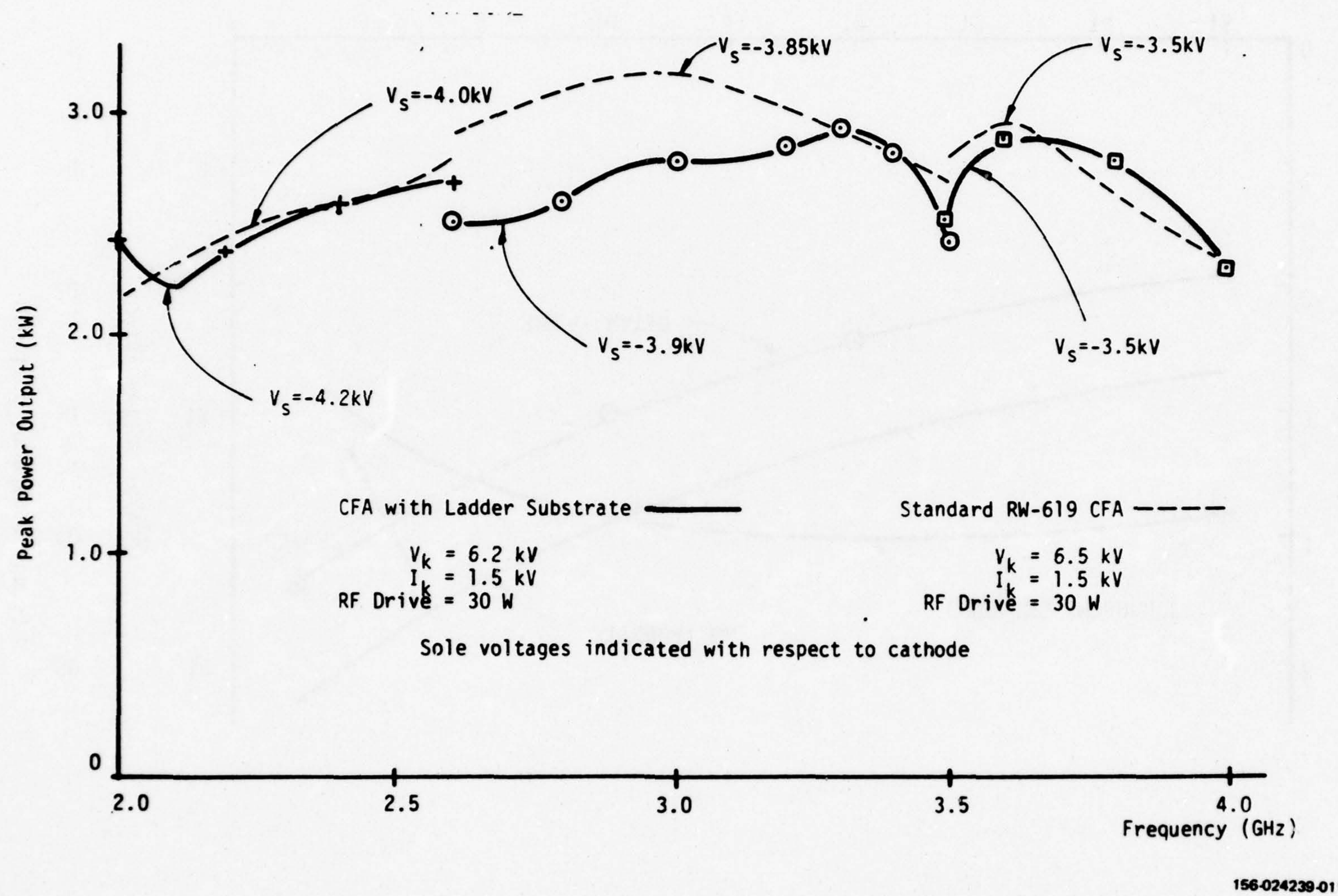


Figure 11. Power Output of CFA No. 1 with Ladder-Shaped Substrate Typical Standard CFA for Comparison.

3.4 Operating CFA No. 2

In the second operating CFA, the circuit design was the same as in the first, except that the substrate was 0.026" thick instead of 0.017". The fixture for bonding the substrate to the ground plane had been modified so that a piece of alumina ceramic was bearing on the assembly on both sides instead of stainless steel. There was no sign of fracturing of the ceramic.

Cold test results are shown in Figure 12. The delay ratio is much lower than in No. 1, and as would be expected the coupling impedance was higher. The attenuation was somewhat less. Consequently, in assembling the tube the line-sole spacing was increased to maintain the same value of βd as before in mid-band. (β is propagation constant, $2\pi f/v_{ph}$, and d is sole-to-line spacing).

Tube operation was seriously limited in peak power to a level of 1000-1500 watts. This could not be improved by reducing duty or pulse duration, or by adjusting operating parameters. A repeat of cold-test measurements showed a significant increase in attenuation. Original measurements were in the range of 2 to 4.5 dB from 2 GHz to 4 GHz; after operation the range was 2.8 to 6 dB.

A test was made to determine whether, as suspected, arcing between circuit and ground was occurring. Another E/F-band CFA was used to feed RF power into the ladder substrate CFA. The latter had no dc power nor magnetic field applied. The appendage ion pump was observed to indicate possible arcs. Some indication of gas was observed below 1.5 kW peak, and severe gassing was observed at 3 kW peak.

A measurement of output power as a function of frequency is shown in Figure 13, at a power level for which the tube was stable.

There is no obvious explanation for the RF arcs. Unlike the first ladder substrate tube, the substrate of this tube was free of cracks at the time of

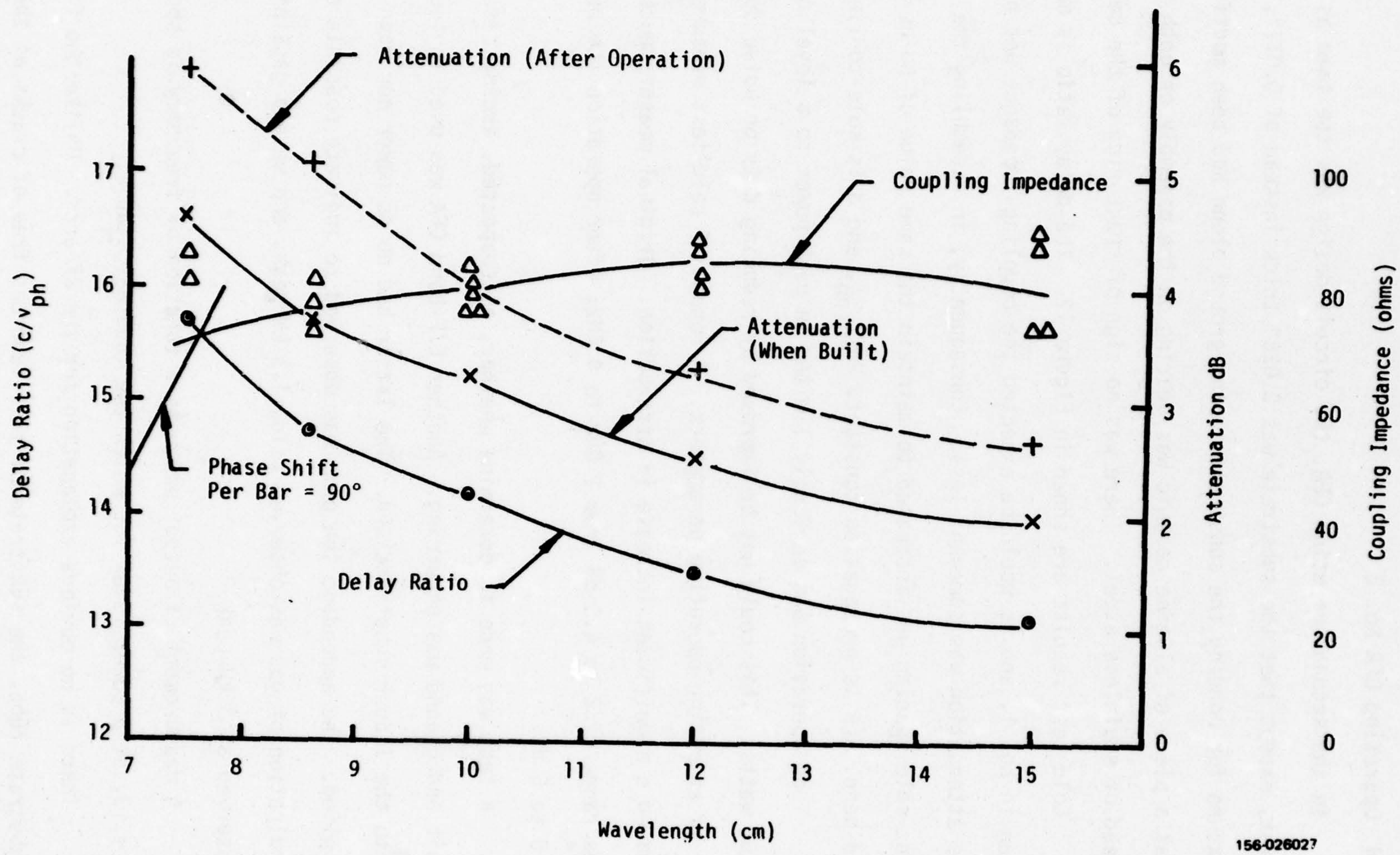


Figure 12. Cold-Test Results of Operating E/F-Band CFA No. 2

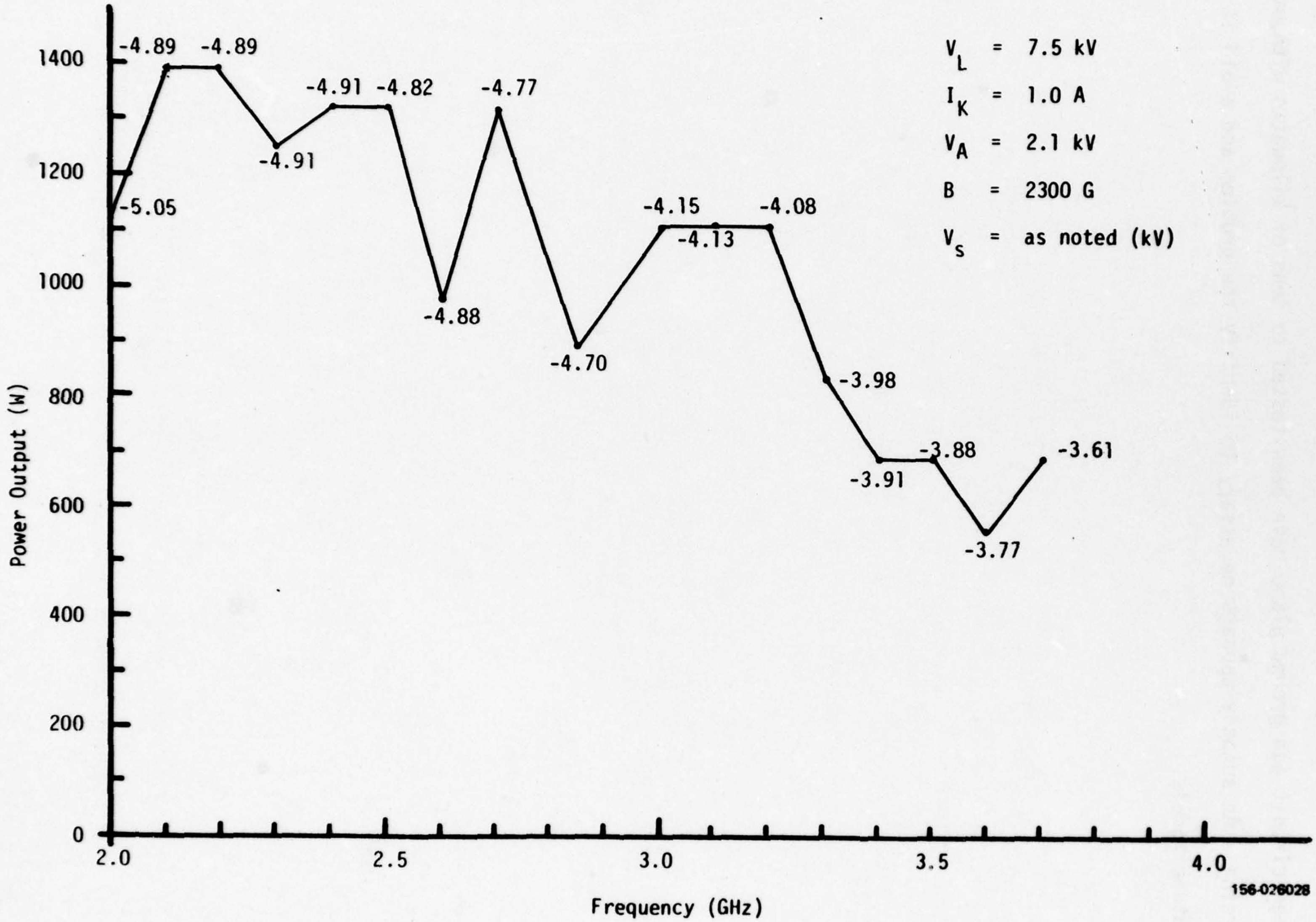


Figure 13. Power Output of Operating E/F-Band CFA No. 2

assembly. Other CFA's with less than half as much insulator separation between circuit and ground plane have been tested to tens of kilowatts without arcing. An autopsy appears necessary to identify the problem and avoid it in future models.

SECTION IV

I/J-BAND

4.1 Cold Test Models

The initial design for a cold-test model of the I/J-band circuit was based on ERADCOM data on S-band cold-test models. A scale factor of 4/17 in wavelength was applied. The pitch was then increased from the value obtained from this scale factor by assuming a reduction in delay ratio, c/v_{ph}, from 18.4 (at 90° phase shift per bar) to 12. This provides a decrease in attenuation, a critical parameter in I/J band, and a more easily fabricated structure. The thickness of the substrate was chosen to maintain the same value of thickness to bar width. The results of these design calculations are as follows:

	ERADCOM DATA	I/J BAND
Frequency Range (GHz)	2-4	8.5-17
Delay Ratio ($\phi=90^0$)	18.4	12
Pitch (inch)	0.050	0.018
Bar Width (inch)	0.025	0.009
Slot Length (inch)	0.450	0.106
Substrate Thickness (inch)	0.017	0.006

The selection of a delay ratio of 12 for initial tests was somewhat arbitrary. It was based on the assumption of 8 kV for cathode-to-ground (circuit) voltage. It is desirable that the beam voltage, V_o, be less than one fourth of cathode to ground voltage, where:

$$V_o = \frac{1}{2}\frac{m}{e}v_e^2$$

m = mass of electron

e = charge of electron (magnitude)

v_e = electron velocity (approximately equal to phase velocity)

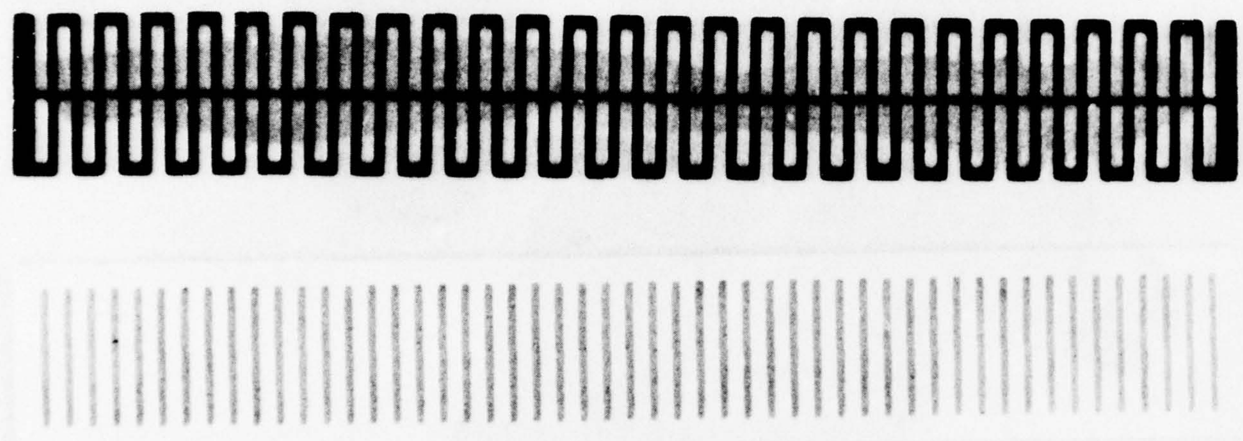
For $v_e = c/12$, V_o is about 1800 V. For optimum performance of an operating device, these are trade-offs relating to attenuation and rate of gain. A lower value of cathode voltage and correspondingly greater beam current leads to greater rate of gain. The increase in rate of gain is greater than the increase in attenuation which accompanies the necessary reduction in phase velocity and in pitch[6]. These trade-offs are more effectively considered by large-signal calculations.

The fabrication of cold-test models 50 bars long was limited by difficulties in laser cutting these very small substrates. Fragility and breakage during fabrication and in subsequent handling were the great obstacles. The first successful substrate was 0.010" thick and was not metallized. It was cemented to a ground plane, and a photo-etched meander circuit 0.002" thick was cemented on top. The substrate and meander line are shown in Figure 14. The assembly, mounted in a fixture for making connections, is shown in Figure 15. Results obtained for delay ratio are shown in Figure 16. Matching at the high end of the band was poor so that attenuation can only be estimated. At 8.5 GHz, attenuation was 2.5 dB; at mid-band (12.75 GHz) it was approximately 3.5 dB, at 17 GHz it was estimated to be between 6 and 7 dB.

The second cold test model was built with a laser-cut substrate which had been metallized and the meander pattern photo-etched before laser cutting. The assembly was diffusion bonded using an added copper meander in the same manner as described for the E/F-band operating tubes. It was subsequently necessary to etch away some excess metallizing from the ceramic. One bar was also damaged in handling.

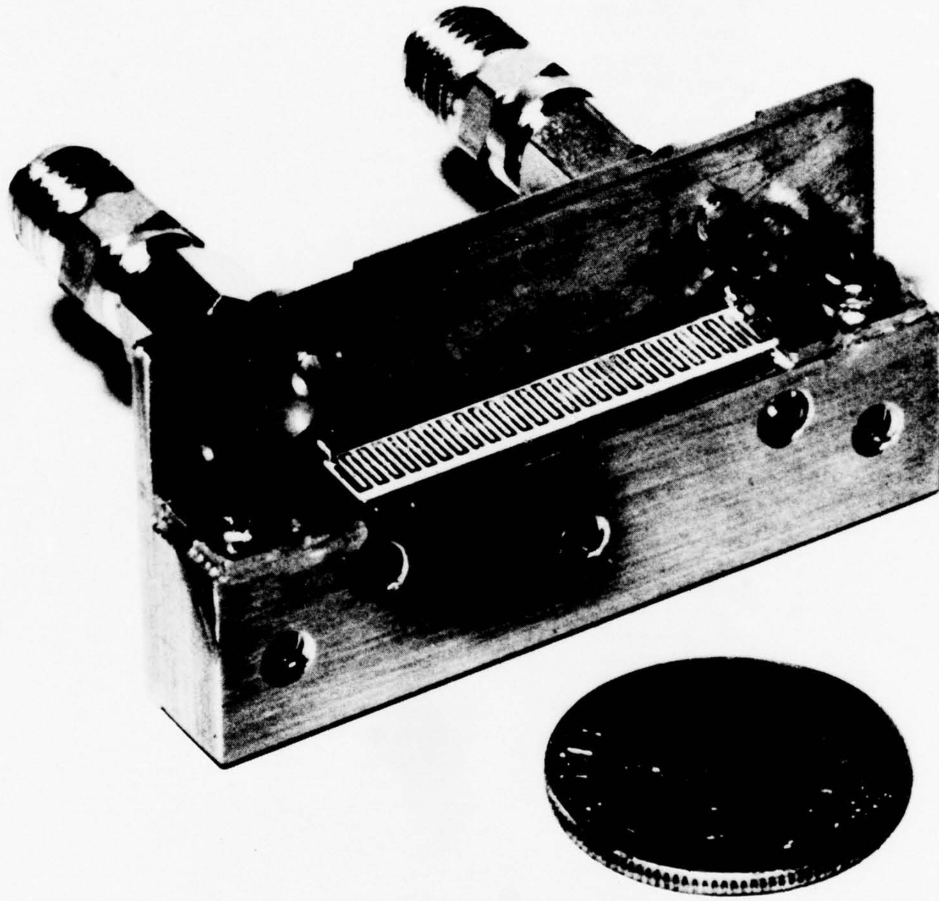
Test results showed much greater attenuation than the first cold test model, and the delay ratio was much greater. The delay ratio is shown in Figure 17. There appeared to be slightly different values of phase velocity when

[6] R.J. Espinosa, R.R. Moats, "Broad-Band Injected-Beam Crossed-Field Amplifiers", IEEE Transactions on Electron Devices, Vol. ED-24, pp. 13-21, Jan. 1977.



156-024801

Figure 14. Substrate and Meander Line for I/J-Band Cold Test Model.



156-024800

Figure 15. I/J Band Cold-Test Model.

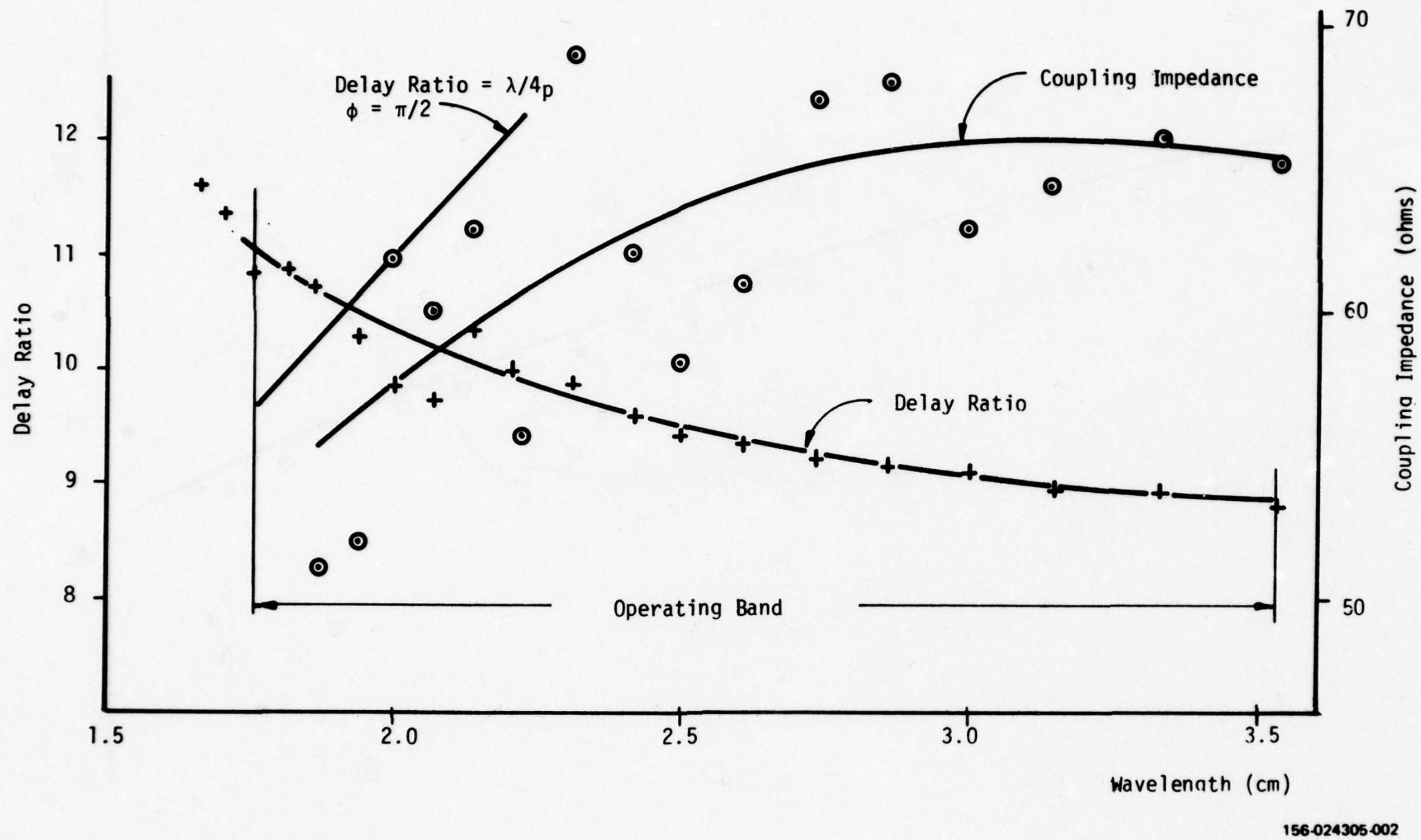


Figure 16. Delay Ratio and Coupling Impedance I/J Band Meander Line on Ladder Substrate, Not Brazed.

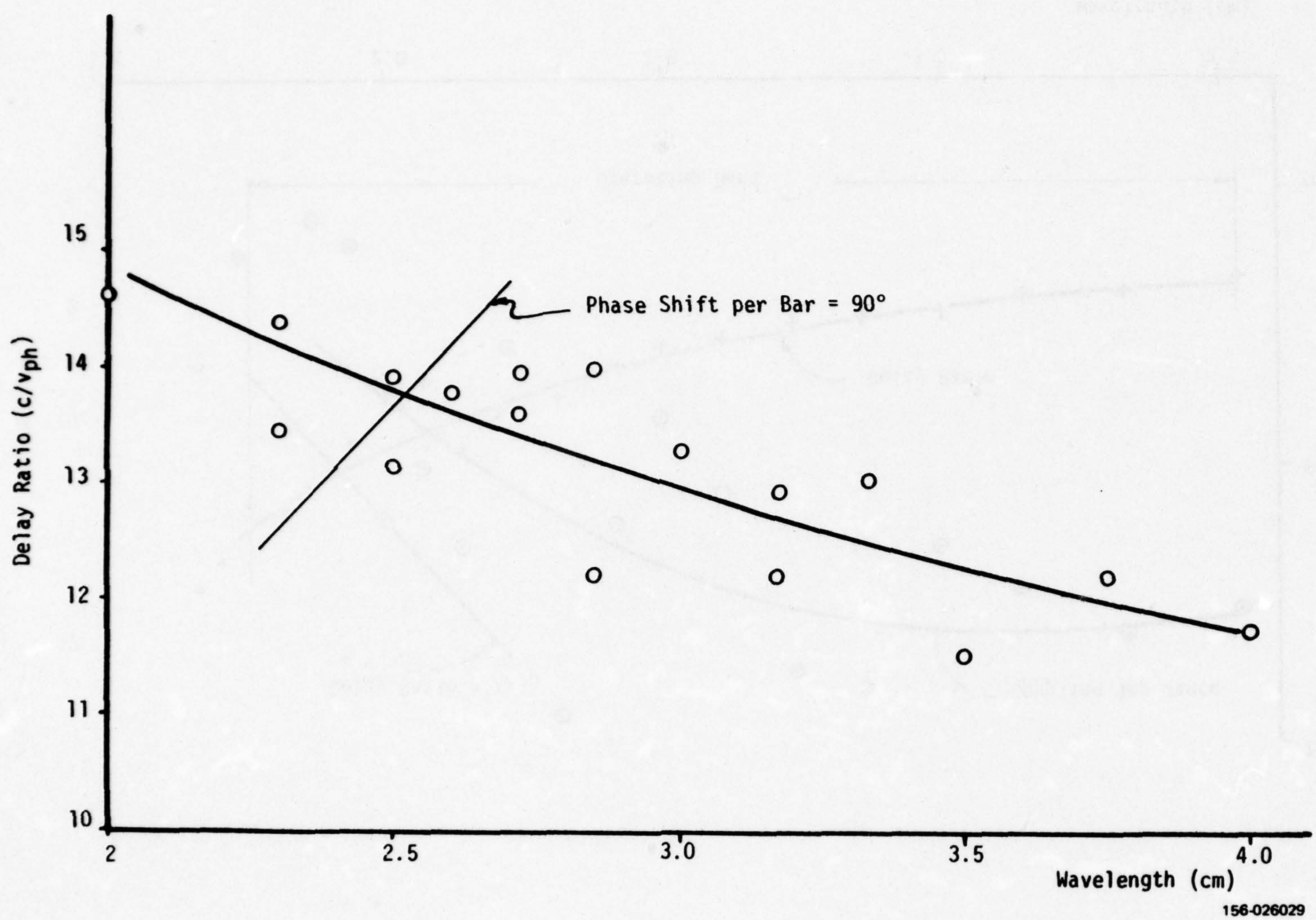


Figure 17. Delay Ratio: I/J Band Cold-Test Model No. 2

observed near one end or near the other. The frequency for 90° phase shift per segment was near 12 GHz, instead of 15.5 GHz as observed in the first cold-test model. Attenuation above 14.5 GHz was too high for reliable measurements to be made.

Measuring attenuation by transmission was not found to be reliable because of even greater difficulty in matching than the first cold-test model. The circuit was loosely coupled and Q measurements were made. The analysis was based on the work of Slater[7]. The attenuation, α, is related to unloaded Q, Q_u, by:

$$\alpha = \pi f / v_g Q_u \quad \text{(nepers/unit length)}$$

where f is frequency and v_g is group velocity. Values of attenuation at resonance points are as follows:

Frequency (GHz)	Attenuation (dB/cm)	Attenuation (dB per delayed wavelength)	Attenuation (dB over length of circuit)
10.69	4.3	0.88	9.8
12.46	3.2	0.54	7.2
13.58	5.8	0.88	13.3
14.28	6.7	0.96	15.2

To examine the electrical parameters of the circuits related to the phase velocity measurements, it is useful to apply the following expression derived from the work of Leblond and Mourier[8].

$$\cos k L = \frac{\cos \phi}{1 + 2(\gamma_1/\gamma_0) \sin^2 \phi}$$

In the above, k is the wave number for a wave propagating along the length L of each bar, ϕ is phase shift per bar, and γ_1 and γ_0 are respectively the

[7]J.C. Slater Microwave Electronics, ch. V, D. Van Nostrand Co., New York,1950.

[8]A. Leblond, G. Mourier, Ann Radioelectricitie, Vol 9, p. 311 (1954)

capacitances per unit length from one bar to each adjacent bar and from one bar to ground. A parameter of interest is k/k_o, where k_o is the wave number in free space, given by $2\pi f/c$. It is possible to match the observed velocity curves to this equation rather accurately for $\phi \leq 90°$ assuming k/k_o is constant, and values of k/k_o and γ_1/γ_o are found. The value of γ_1/γ_o is a measure of dispersion, which is zero for $\gamma_1 = 0$, and becomes progressively larger for larger γ_1/γ_o.

The increased delay ratio and increased attenuation in the second cold test model are both difficult to account for. Electrical parameters derived from cold-test data are compared in Table I for the two E/F-band tubes, a circuit made and tested by ERADCOM personnel, and the two I/J-band cold test models. The value of k/k_o for the first I/J-band cold test model is comparable with E/F-band tube No. 2, where the ratio of thickness to pitch is also comparable. One may assume that the attenuation per bar is proportional to width/pitch. If the difference in the width to pitch ratio is taken into account, the attenuation per bar in the first I/J-band model is about twice that in the E/F-band tubes, which is consistent with surface resistivity varying in proportion to the square root of frequency. The value of k/k_o for the second I/J-band cold test model is much greater than any of the other circuits. Therefore the results are quite difficult to explain, except possibly in terms of inadequate assembly or bonding procedures.

4.2 Gun Considerations

Design of the gun for an I/J band IBCFA depends on interaction space concepts. The interaction space is assumed to be the width of the line, i.e., length of the slots in the substrates plus twice the bar width, or 0.124 inch in this case. The line-sole spacing, d, will be assumed to be such that βd = 4 at the high end of the band (where β is the propagation constant corresponding to 17 GHz). For a delay ratio of 12, and for line-to-sole voltage of 12

TABLE I

Circuit Parameters: Meander Lines on Laser-Cut Substrates

Circuit	t	p	t/p	w	e	k/k_o	γ_1/γ_o	Attenuation (dB per delayed wave-length)
E/F-Band, Tube No. 1	0.017	0.048	0.35	0.436	0.005	1.86	0.11	0.28
E/F-Band, Tube No. 2	0.026	0.048	0.54	0.436	0.005	1.71	0.16	0.25
ERADCOM Model	0.017	0.050	0.34	0.475	0.001	1.94	0.06	0.22
I/J-Band No. 1	0.010	0.018	0.56	0.116	0.002	1.66	0.17	0.38
I/J-Band No. 2	0.006	0.018	0.33	0.116	0.002	2.19	0.14	0.54(1) 0.88(2)

Notes: t = Substrate thickness (in)

p = Pitch (in)

w = Effective circuit width (in)

e = Meander thickness (in)

c/v_{ph} and attenuation at mid band (3 or 12.75 GHz)

except:

(1) 12.46 GHz
(2) 13.6 GHz

kV, the line-sole spacing is 0.037 inch, and the magnetic field is 5100 gauss. This value is about twice that used in present 4-8 GHz IBCFAs, which have a delay ratio range of 12.5 to 14. As an initial assumption, then, it is appropriate to assume a cathode dimension in the direction parallel to electron flow about half of that of the 4-8 GHz tube, or 0.090 inch. If peak current up to 0.5 A is required, then the average current density required of the emitter, assumed to be 0.124 by 0.090 inch, is 6.94 A/cm^2.

For a gridded gun, scaling by a factor of 0.5 from the 4-8 GHz tube, the grid to cathode spacing should be about 0.0035 inch, the grid thickness 0.003 inch, the grid bars no more than 0.002 inch wide, and the pitch between center of bars about 0.012 inch. For a beam current of 0.5 A peak, compared with 1.5 A in the 4-8 GHz tube, the dimensions may be a little larger. Further study is needed. With a grid, the local current density needs to be two to three times as much as the average value across the surface. Peak pulse current densities of 20 A/cm^2 have been easily achieved with dispenser cathodes, and have been achieved also in some recent samples of "Medicus" nickel matrix cathodes. Therefore, the available cathode emission density is not expected to be an immediate problem. For long life, it would be desirable to reduce emission density substantially. The limit on cathode length parallel to electron flow is a somewhat arbitrary one. Previous experience has shown that an excessively long cathode leads to high beam noise and beam instability. Reduction of beam noise is possible by designing the accelerating anode to conform to the Kino long gun configuration[9]. Further understanding of this pro-

[9] G.S. Kino, "A New Type of Crossed-Field Electron Gun," Crossed-Field Microwave Devices, (E. Okress, ed.) Vol. 1, pp. 164-177, Academic Press New York, 1961.

blem may be provided by recent and current work on crossed-field guns supported by Air Force Office of Scientific Research[10,11,12].

[10]G.P. Kooyers and E.K. Shaw, "The Study of Noise Phenomena in Crossed-Field Electron Beams", Interim Scientific Report, AFOSR Contract No. F49620-77-C-0061, February 15, 1977 to February 15, 1978.

[11]F.W. Crawford, "Study of Noise in Crossed-Field Electron Guns", Annual Report No. 1, AFOSR Research No. 77-3306, May 1, 1977 to April 30, 1978,SU-IPR Report No. 745 June, 1978.

[12]I.P. Shkarofsky, "Study of Noise in Crossed Field Microwave Devices" Interim Science Report (1977-1978), AFOSR Contract No. F49620-77-C-0106.

4.3 Output Circuit

The simplest possible method of input and output connection to a meander circuit is by means of coaxial lines. Coaxial windows capable of 5 kW or more peak power handling capability in the 4-8 GHz band may be scaled in frequency. Windows of the resulting dimensions in theory will be capable of handling less than one-fourth as much peak power, based on voltage gradients. They could therefore be marginal in performance. Coaxial windows with larger diameters are subject to higher-order modes, or "ghost" modes, which can appear as a result of slight asymmetries. The result is increased reflection. Nevertheless, such windows are under investigation for I/J-band at Northrop, initially for I/J-band TWT's.

An alternative is a waveguide window, which presents much more difficulty than a coaxial window. No kind of suitable "thick" window (i.e., thickness of the same order of magnitude as one-half guide wavelength, or greater) is foreseen for an octave band. A "thin" window is necessary. At 17 GHz, a wavelength in beryllium oxide ($\varepsilon_r = 6.5$) is 0.272 inch. A value of 0.020 inch thick would be a reasonable starting point, and beryllia ceramics of high quality in this thickness or even thinner are commercially available. Other materials may also be considered.

For optimum power handling and low attenuation in the output transmission circuit, WRD750D24 waveguide is desirable. A waveguide transformer from the 50 or 60 ohms of the circuit, or 50 ohms in a coaxial output, is necessary. In the range of 8.5 to 17 GHz, the ratio of guide wavelengths is almost 3:1, and this must be taken into account in the transformer design.

An upper limit of 3.5:1 in impedance level ratio between guide and delay line was assumed, based on impedance calculations in the guide (about 175 ohms at midband). Using the work of Cohn,[13] it is calculated that the ideal maximum vswr for a system of three quarter-wave transformer sections is 1.15:1; for four quarter-wave transformer sections the ideal maximum vswr is 1.07:1. It is a straight-forward process to establish the initial design of waveguide transformer using the procedure described by Hensperger[14]. In addition to such calculations, there is some Northrop experience available to be drawn upon in the transition from coaxial to ridge waveguide, including the present E/F band and G/H band IBCFAs, in backward wave oscillators, in a J-band IBCFA which used a transition from line-to-waveguide inside the vacuum envelope,* and in an I/J-band TWT now being designed. The last of these may be directly applicable to the I/J-band CFA.

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[13] S.B. Cohn, "Optimum Design of Stepped Transmission Line Transformers", IRE Transactions on Microwave Theory and Techniques, Vol MTT-3, No. 3, p.16, April, 1955.

[14] E.S. Hensperger, "Broadband Stepped Transformer from Rectangular to Doubleridge Waveguide", IRE Transactions on Microwave Theory and Techniques, Vol. MTT-6, p. 311, July, 1958.

*Contract No. F33615-72-C-1356, U.S. Air Force Avionics Laboratory.

SECTION V

SUMMARY AND CONCLUSIONS

The technology for constructing meander circuits on laser-cut shaped substrates has been demonstrated. The sequence of operations which has been used on circuits built so far was:

(1) Metallize coupon, both sides.

(2) Etch meander on one side.

(3) Laser-cut between bars of meander

(4) Bond to co-expansive ground plane.

Breakage during and after laser cutting has been a problem, especially for I/J band dimensions. Based on preliminary experiments, an alternative sequence, in which operations (3) and (4) in the above listing are interchanged, appears feasible for I/J-band dimensions. The laser-cutting is performed after the substrate is bonded to the ground plane.

Performance of an E/F-band operating CFA was comparable with similar CFA's in the 2-4 GHz band in which conventional circuit construction was used. A second E/F-band operating CFA was limited in peak output power, apparently from RF arcs due to as yet undetermined causes.

An unbrazed I/J-band cold-test model showed electrical characteristics which will in principle be suitable for operating CFA's. Some dimensional modifications are foreseen. An I/J-band cold-test model which incorporated a metallized substrate bonded by copper-to-copper diffusion to a meander circuit and co-expansive ground plane showed excessively high attenuation and phase velocity much lower than predicted. These anomalies have not yet been explained.

An improved cold-test model is to be designed and built which will overcome the matching deficiencies of previous cold-test models, and provide means of establishing a good design for input-output match for operating I/J-band

CFA's. Input/output circuits including vacuum windows, discussed previously in this report, are to be tested. The gun designs which have been described in this report will be embodied in hardware and tested in Northrop's crossed-field beam tester, developed under Air Force sponsorship*.

The above tasks, which are immediate outgrowths of the work reported here, are necessary for the development of an operating I/J-band CFA. The next task in over-all CFA design is to make large-signal calculations based on the best estimates of circuit properties derived from presently available cold-test data, and which will be revised later by more definitive cold-test data, mechanical and thermal design, then construction and testing of operating models will follow.

The work reported here, then, has defined the areas of effort which must be concentrated on to achieve successful design and construction of operating I/J-band CFA's.

*Contract F33615-75-C-1033 and F33615-78-C-1435, Air Force Avionics Laboratory.

SECTION VI

FUTURE WORK TO BE PERFORMED

The future work to be performed, summarized here, is to be carried out under a follow-on contract, No. DAAB07-78-C-2981, which has already been awarded. The latter contract requires construction and testing of operating I/J-band CFA's. It also requires construction and testing of two more operating E/F-band CFA's, which will also be evaluated for a possible additional requirement of a 2 kW peak power mode, 3-3.6 GHz, with 25 dB gain, for phased array applications.

The first operating E/F-band CFA is to be re-tested to determine whether any design modifications are required for the phased-array performance requirements. Possible required modifications are increased circuit length and added attenuation near the input to increase gain.

The cause of the apparent RF arcing in the second E/F-band operating tube needs to be identified to avoid such problems in the future.

The cause or causes of anomalous results in the second I/J-band cold-test circuit must be identified. One area to be investigated is the metal-ceramic interface. Other possible means of reducing circuit losses include:

(1) Thicker substrate, with a compromise on dispersion.

(2) Circuit overhang, to reduce high current concentration near the ceramic-to-circuit interface, again with a compromise on dispersion.

(3) Other variations of circuit and/or substrate dimensions.

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